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TITLE OF THE INVENTION

METHOD AND APPARATUS FOR COMPENSATING FOR AN ECHO SIGNAL COMPONENT IN TELECOMMUNICATION SYSTEMS

FIELD OF THE INVENTION

The present invention relates generally to the field of data communications and in particular to a circuit and method for compensating for transmission echo in a telecommunications system.

BACKGROUND OF THE INVENTION

Data communication systems are commonly used to transmit and/or receive data between remote transmitting and receiving locations. A central facet of any data communications system is the reliability and integrity of the data communicated. Ideally, the data, received at the receiving location is identical to the data transmitted from the transmitting location. Practically

however, the effects of transmission echo (i.e., reflection of the transmitted signal such that it appears as part of the received signal) can cause the data which is being received to be corrupted or lost.

Signals received by a modem typically have a large dynamic range and may be affected by transmission echo. As modems transmit higher bandwidth signals over traditional twisted pair copper telephone lines, echo has a greater effect on modem performance. For example, a broadband Digital Subscriber Line (xDSL) operating over twisted pair copper wires, such as Asymmetric Digital Subscriber Line (ADSL) technology, uses signals transmitted at up to and over two megahertz which are typically attenuated by as much as 90 dB before being received by the modem. Additionally, the upstream and downstream data channels may use overlapping frequencies. When overlapping frequencies are used, the modem transmission echo must be compensated for, as it will have a greater amplitude than the received signal in the same frequency spectrum. In ADSL systems, the frequency spectrum is assigned to the various communications channels conveyed over the twisted pair using a splitter. The lowest 4kHz of bandwidth is reserved for use by analog devices such as common telephones of the baseband Plain Old Telephone Service (POTS). A medium frequency range full duplex channel in the frequency range of 30 kHz to 140 kHz may be defined to carry upstream ADSL data and downstream ADSL data having a typical data rate in the 16 kbps to 640 kbps range. A high frequency channel that uses frequencies in the 140kHz to 1104 kHz range carries downstream data having a typical data rate in the 1.536 Mbps to 6.144 Mbps range. Accordingly, the medium frequency upstream and downstream data channels used by ADSL modems may use overlapping frequency ranges.

Modems and other communication systems typically include a hybrid coupling circuit

for connecting to the local loop which then connects to the telephone company central office. Additionally, the transmitted and received signals may be transmitted on overlapping frequencies as in the case of ADSL. Accordingly, an ADSL modem must incorporate a suitable hybrid circuit to attenuate or compensate for its own transmission echo in order to maximize the dynamic range of the receive path of the ADSL modem. The received signal is detected at the secondary side (the side of the transformer connected to the modem and hybrid circuit) of the line transformer. The transmitted echo signal (which has had its characteristics affected by the line transformer and the line itself) is inseparable from the received signal at the secondary side of the line transformer. In ADSL applications, it is likely that the local loop will be sufficiently long such that the effect of the telephone company central office devices or other devices connected to the ADSL modem will be negligible. However, the transmitted echo signal may oftentimes be affected by the telephone company central office devices, requiring compensation by the line compensation circuit of the balanced hybrid circuit.

Simultaneously with the detection of the received signal, a sample of the transmitted signal is taken from the output of the modem line driver and this sample is processed in order to obtain a replica of the transmitted echo signal. The replica of the transmitted echo signal is then subtracted from the received signal. Accordingly, the effectiveness of the attenuation of the transmission echo signal is related to how well the reconstructed echo signal matches the actual transmission echo signal. Accordingly, the received signal has an improved received to transmit echo signal ratio when the echo compensation circuit of the hybrid circuit closely replicates the transmission echo.

Prior art hybrids and circuits used to compensate for transmission echo signals in

modems have several disadvantages, such as the use of a large number of components. Additional disadvantages of prior art devices include the use of active circuitry for transmission echo reconstruction and subtraction that can increase distortion and nonlinearity.

SUMMARY OF THE INVENTION

The invention relates to a balanced hybrid coupling circuit and method of using the hybrid in a full duplex modem device to attenuate the transmission echo of the modem when receiving a signal from another communications device over a communications channel such as common telephone lines.

In general, the balanced hybrid coupling circuit of the present invention receives a differential transmission signal from a pair of differential drivers in the modem. A line transformer couples the differential transmit signal to the local loop twisted pair copper cable. The received signal from the far end is received on the same local loop twisted pair copper cable and is also coupled to the modem receiver by the line transformer.

Because the transmit and receive signals operate on overlapping frequencies, the transmit signal is sampled, e.g., across a sampling resistor, and subtracted from the line signal to reconstruct the received signal. Because the modem transmission will create an echo signal due to the effects of the line transformer and local loop, the present invention will simultaneously sample the transmitted signal across two RC networks that respectively simulate the effects of the line transformer and the local loop. These RC networks produce components of a transmission echo signal replica that are also subtracted from the line signal to more accurately isolate the received signal which is then supplied to the differential receiver in the modem.

The first RC network of each half of the balanced hybrid circuit is used to compensate for the transmission echo effect of the line transformer by simulating the transmission echo effect of the line transformer and producing a component of a transmission echo replica signal that approximates the transmission echo produced by the line transformer. The sample is effectively inverted by actually sampling the transmission signal of the opposite transmitter of the differential transmitter pair. The transmission echo replica signal component is subtracted from the line signal to isolate the received signal.

The second RC network of each half of the balanced hybrid circuit is used to compensate for the transmission echo effect of the line or local loop twisted pair copper wire by simulating the transmission echo effect of the line and producing a component of a transmission echo replica signal that approximates the transmission echo produced by the line. The transmission echo replica signal component is subtracted from the line signal to further isolate the received signal.

Additionally, in a further embodiment where the effect of the telephone company central office devices or other devices connected to the ADSL modem is not negligible, that effect can be compensated for by modifying the balanced hybrid circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the present invention is described herein with reference to the drawings wherein:

FIG. 1 is a schematic diagram of a preferred balanced hybrid circuit;

FIG. 2 is a schematic diagram of a single ended (unbalanced) simplification of the transmit circuit shown in FIG. 1 assuming an ideal transformer and a constant Ohmic line

impedance;

FIG. 3 is a schematic diagram of a single ended (unbalanced) simplification of the hybrid circuit shown in FIG. 1 assuming an ideal transformer and a constant Ohmic line impedance;

FIG. 4 is a schematic diagram of a single ended (unbalanced) simplification of the transmit portion of the hybrid circuit shown in FIG. 1 assuming a real transformer with secondary inductance and a constant Ohmic line impedance;

FIG. 5 is a schematic diagram of the input impedance of the twisted pair local loop;

FIG. 6 is a schematic diagram of a single ended (unbalanced) simplification of the transmit portion of the hybrid circuit shown in FIG. 1;

FIG. 7 is a schematic diagram of a single ended (unbalanced) hybrid circuit; and

FIG. 8 is a schematic diagram of a balanced hybrid circuit.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In general, the balanced hybrid coupling circuit of the present invention transmits and receives a differential signal through a line transformer. The echo compensation hybrid circuit creates a replica of the transmission echo signal and subtracts the echo replica signal along with the transmitted signal from the line to obtain the true received signal.

A preferred embodiment of the present invention is described in detail below with reference to the figures. The figures will be used to explain the theory of operation of the hybrid circuit using several simplifications of the circuit of the preferred embodiment shown in FIG. 8.

Referring to FIG. 1, therein is illustrated an overview of the balanced hybrid echo compensation circuit **10**. The differential transmission signals **1, 3** are received at the two respective

line drivers **2, 4**. The transmission signals are sampled by the respective sampling resistors **Rs1, Rs2** at the output of the line drivers **2, 4** and coupled to the line **16** by line transformer **14**. The sampled transmission signal is input to the echo compensation circuit **12** which produces a compensated received signal **18**.

Referring to FIG. 2, therein is illustrated a single ended (unbalanced) simplification of the transmit portion of the hybrid circuit shown in FIG. 1 assuming an ideal transformer **14** and a constant Ohmic impedance for line **16.** An ideal transformer transforms impedance from its primary winding (line side) to its secondary winding (hybrid side) according to its turns ratio and has an infinite parallel inductance. Accordingly, the transmit portion of the simplified hybrid circuit includes a transmitted signal source **Vtx** in series with a sampling resistor **Rs1** and a load resistor **Rload** which equals the resistance of the line **16** transformed to the secondary winding of the transformer. The voltage at the load resistor, at node **Vload,** is determined by the equation:

$$\text{Vload} = \text{Vtx}\ (\text{Rload}/(\text{Rs1}+\text{Rload})). \qquad \text{(Eq. 1).}$$

The parameter "return loss" is a measure of how close the modem output impedance matches a reference impedance, which is defined as 100 Ohms in the standard specification for an ADSL modem. High return loss is an advantageous characteristic of a modem, indicating a proper impedance match. In order to achieve a high return loss value, the sample resistor **Rs1** is chosen to equal the load resistance value **Rload**.

Referring to FIG. 3, therein is illustrated a single ended (unbalanced) simplification of the hybrid circuit shown in FIG. 1 that is used to describe the echo compensation for the real component of the load reflected through the transformer **14**. FIG. 3 illustrates a simplification assuming an ideal transformer **14** and a constant Ohmic impedance for line **16.** As discussed below,

the line **16** is assumed to have a very large attenuation that masks the influence of the impedance of any modem or other communications device connected to the other end of the line **16**. A current limiting resistor **R32** is placed between the **Vload** node and the **Vrx** node. The resistor **R32** has a value chosen to be much greater than the value of **Rs1** so that it does not significantly load the **Vload** node. As described herein, a sampling signal can be taken from the complementary signal node of the balanced circuit as shown in FIG. 8 where node **-Vrx** is connected to **C78'**. Accordingly, inverter **34** is used in the simplified circuit of FIG. 3 to denote the configuration in the balanced circuit where the sample signal is taken from the complementary signal of the balanced circuit. Accordingly, as **Rs1** approaches the value of **Rload**, the value of **Vload** approaches the value **Vtx** / 2. Because **Rs1** is preferably equal to **Rload**, equation 1 can be simplified to:

$$\text{Vload} = \text{Vtx}/2. \qquad \text{(Eq. 2).}$$

Summing the sample of **Vload** through current limiting resistor **R32**, and the sample of **-Vtx** via inverter **34** through resistor **R36** (which is preferably substantially equal to 2***R32**) will result in a voltage null at the **Vrx** node.

For example, if the current flowing through **R32** is designated I32 and the current through **R36** is designated I36, we have the following equation assuming that the transmission echo at **Vrx** is zero:

$$\text{I32} = (\text{Vtx} * ((\text{Rload} \,||\, \text{R32}) / (\text{Rs1} + \text{Rload} \,||\, \text{R32}))) * 1/\text{R32} \qquad \text{(Eq. 3).}$$

And after algebraic manipulation, the equation is restated as follows:

$$\text{I32} = \text{Vtx} * (\text{Rload}) / (\text{Rs1} * \text{R32} + \text{Rload} * (\text{Rs1} + \text{R32})) \qquad \text{(Eq. 4).}$$

The other current path into node **Vrx** is through **R36** described as follows:

$$\text{I36} = \text{Vtx} * 1/\text{R36} \qquad \text{(Eq. 5).}$$

Therefore, in order to null the transmission signal at node **Vrx**, and accounting for the inverter **34**,

$$I32 = I36 \qquad \text{(Eq. 6).}$$

And after algebraic manipulation, we have:

$$R36 = Rs1 * R32 / Rload + Rs1 + R32 \qquad \text{(Eq. 7).}$$

As discussed below, a desirable deign goal is impedance matching whereby Rs1 is equal to Rload. If R32 is chosen to be much greater than Rs1 (R32 >> Rs1) in order to minimize loading of the circuit by R32, a design rule for the balanced hybrid echo compensation circuit is developed as:

$$R36 = 2 * R32. \qquad \text{(Eq. 8).}$$

As described below, the resistor **R36** of the simplified circuit corresponds to resistor **R74** in the final balanced hybrid compensation circuit of FIG.8 as part of the RC network which compensates for the echo effect of the transformer **14.**

Referring to FIG. 4, therein is illustrated a single ended (unbalanced) simplification of the hybrid circuit shown in FIG. 1 that is used to describe the echo compensation for the effect of the secondary winding of a real transformer. FIG. 4 illustrates a simplification assuming that the transformer **14** is not an ideal transformer, but rather a non-ideal transformer **14** with a secondary inductance **L** and a constant Ohmic impedance **Rload** for line **16**. The inductance **L** of the transformer is simplified as an inductance connected in parallel with **Rload**. Accordingly, to compensate for the effect of the line transformer **14** secondary inductance **L**, the sample of **Vtx** that is subtracted from **Vrx** is modified by capacitor **C**. The inductor **L** affects **Vload** by adding a zero at the origin and a pole at the frequency that corresponds to the RL time constant of **L** and the parallel combination of **Rs1** and **Rload**. In the final balanced circuit, the sample is taken from the

complementary transmission signal. Accordingly the compensating sample should have a signal with the same amplitude, but with opposite polarity. As described below, the capacitor **C** of the simplified circuit corresponds to capacitor **C78** in the final balanced hybrid compensation circuit of FIG. **8** as part of the RC network which compensates for the echo effect of the transformer **14**.

Referring to FIG. 5, therein is illustrated a simplification of the input impedance of the twisted pair local loop line **16**. An actual twisted pair line has a characteristic impedance that is complex and is a function of the frequency of the transmitted and received signals. The simple model of such an impedance is shown in FIG 5, and includes **Rline1** in series with the parallel combination of **Rline2** and **Cline**. The characteristic impedance of the local loop twisted pair copper wire varies according to the physical parameters such as the distance from the telephone company central office, wire gauge and number of twists per inch. Accordingly, there are differences in line impedance in different countries and as between different lines in a country. A regulatory agency of a country may specify a line impedance value required of the telephone company and in such instance the value of a typical line impedance is known a priori. Additionally, the line **16** is assumed to have attenuation that masks the influence of the impedance of the equipment at the other end of the line **16**. If a communications device attached to the other end of line **16** has an impedance influence that is not negligible, the impedance of the line **16** can be modeled to consider such communications device impedance.

Referring to FIG. 6, therein is illustrated a single ended (unbalanced) simplification of the transmit circuit shown in FIG. 1, similar to the simplification shown in FIG 2, but instead having a complex load impedance **Zload**. As can be seen from FIG. 5, the magnitude of the load impedance decreases as the frequency increases. Therefore, to compensate for the effect of the line

impedance on the transmission signal **Vtx**, the **Vtx** sample will be processed to provide an echo replica signal that compensates for the frequency dependance of the line impedance. The replica signal will be created using a second RC network as described below.

Referring to FIG. 7, therein is illustrated a single ended (unbalanced) hybrid circuit having two RC branches which compensate for the transmission echo effect of the line impedance and line transformer, respectively. The first RC network of each half of the balanced hybrid circuit is used to compensate for the transmission echo effect of the line transformer and includes resistor **R74** in series with capacitor **C78** as described above with reference to FIGs. 2-4. The second RC network of each half of the balanced hybrid circuit is used to compensate for the transmission echo effect of the line or local loop twisted pair copper wire and includes resistor **R72** in series with capacitor **C76** as described above with reference to FIGs. 5 and 6.

Referring to FIG. 8, therein is illustrated a complete schematic diagram of the balanced hybrid echo compensation circuit. The inverter **34** that is used in FIG. 7 to denote a connection to the complementary circuit is not used in Fig. 8 because the actual connection between node **Vrx** and **C78** and the connection between node **-Vrx** and **C78'** are shown. The balanced hybrid coupling circuit receives a differential transmission signal from a pair of differential drivers **2,4**. The line transformer **14** couples the differential transmission signal output by the line drivers **2,4** through sampling resistors **Rs1, and Rs2** and then to the local loop twisted pair copper cable line **16**. The hybrid receives a signal that is transmitted on the same local loop twisted pair copper cable line **16** and is also coupled to the modem receiver by the line transformer **14**. The following description relates to one half of the balanced hybrid, but as can be appreciated, the other half of the circuit denoted with prime values in FIG. 8 operates in an identical manner.

Because the transmit and receive signals operate on overlapping frequencies, the transmit signal itself must first be subtracted. This is achieved by sampling the transmit signal across a sampling resistor **Rs1** through current limiting resistor **R32**. Resistor **R32** has a much greater value than **Rs1** in order to minimize any loading effect. The sampled transmit signal is subtracted from the line signal to create the received signal isolated from the transmission signal on the local loop. Because the modem transmission also creates an echo signal due to the effects of the line transformer **14** and local loop line **16**, the hybrid circuit simultaneously samples the transmitted signal **Vtx** across two RC networks **R72, C76** and **R74, C78** which respectively simulate the effect of the line transformer and the local loop. These RC networks produce components of a transmission echo signal replica that are also subtracted from the line signal to further isolate the received signal **Vrx** which is then supplied to the differential receiver **82** in the modem.

The first RC network, the line transformer compensation circuit, **R74, C78** having resistor **R74** and capacitor **C78,** is used to compensate for the transmission echo effect of the line transformer, by simulating the transmission echo effect of the line transformer and producing a component of a transmission echo replica signal that approximates the transmission echo produced by the line transformer **14**. The sample is effectively inverted by actually sampling the transmission signal **-Vtx** of the opposite transmitter of the differential transmitter pair. The transmission echo replica signal component is subtracted from the line signal to isolate the received signal **Vrx.**

The second RC network, the line compensation circuit, **R72, C76** having resistor **R72** and capacitor **C76,** is used to compensate for the transmission echo effect of the line (or local loop twisted pair copper wire and any non-negligible communication device effect) **16**, by simulating the transmission echo effect of the line **16** and producing a component of a transmission echo replica

signal that approximates the transmission echo produced by the line. The transmission echo replica signal component is subtracted from the line signal to further isolate the received signal **Vrx.**

Additionally, if the effect of the telephone company central office devices or other devices connected to the ADSL modem is not negligible, that effect can be compensated for by modifying the balanced hybrid circuit. The effect of any other device connected to the line can be compensated by including their electrical models at the final stage of the balanced hybrid circuit design when the balanced hybrid circuit components are optimized. A typical line impedance table is shown below. The line impedance table could be modified to include the electrical characteristic of any other device connected to the line.

TABLE 1

Frequency (MHz)	Z (Ohm)	Phase (Deg.)
.005	301.2	-280.8
.01	220.6	-191.8
.015	186.5	-151.5
.02	167	-126.8
.025	154.5	-109.9
.03	145.7	-97.4
.035	139.2	-87.5
.04	134.3	-79.6
.05	127.3	-67.5
.06	122.5	-58.7
.07	119.2	-52
.08	116.8	-46.8
.09	115	-42.6
.1	113.6	-39.1
.12	111.5	-33.8
.14	110.1	-29.9
.16	109.2	-26.9
.18	108.4	-24.6
.2	107.8	-22.8
.25	106.7	-19.5
.3	105.9	-17.3
.4	104.8	-14.6
.5	103.9	-12.9
.6	103.1	-11.7
.7	102.5	-10.9
.8	101.9	-10.2
1.0	100.9	-9.1

The component values of the balanced hybrid circuit can then be optimized to provide optimal echo compensation using commercially available circuit optimization software such as the "Super Star" package available from Eagleware Corporation.

Several design rules are described which are preferably utilized to optimize the effectiveness of the above described balanced hybrid echo cancellation circuit. The value of **R32** should be much larger than **Rs1** for minimal loading of the transmitted signal.

The transformer inductance **L** is chosen according to the lowest working frequency to minimize its attenuation at the lowest working frequency and to obtain adequate frequency matching at the lowest frequency used in order to achieve a high return loss as usually required by relevant industry and government standards.

The resistor **R74** is selected such that the resistance value is lower than the value of **R72** because the current through resistor **R74** is the main hybrid signal injection route. The signal current injected through resistor **R72** has a lower value than that through **R74** so that it lowers the total signal current injected into node **Vrx** by injecting a smaller current with reverse polarity. Accordingly, **R72** has a higher resistance value than **R74**.

Furthermore, the critical frequency of the transformer compensation RC network, **R74, C78** is selected such that it is lower than the critical frequency of the line compensation RC network, **R72, C76** such that the former influences the hybrid operation at the transformer cutoff frequency at the lowest working frequency. The line compensation RC network, **R72, C76** affects the signal injection at a higher frequency where it compensates for the impedance change of the line with varying frequency.

Additionally, the value of resistor **R74**, is selected such that it is twice the resistance

of **R32** so that the voltage at node **Vtx** is approximately twice the voltage as at **Vload**. Accordingly, to achieve adequate rejection of the transmission signal **Vtx** at node **Vrx**, **R74** should be approximately twice as large as **R32** as described above in relation to the analysis of the circuit simplification shown in Figure 3.

According to the preferred embodiment of the present invention, there are two current paths into the received signal node **Vrx.** The first current path includes the first RC network **R74, C78** which compensates for the transmission echo effect of the line transformer. The second current path includes the second RC network **R72, C76** which compensates for the transmission echo effect of the local loop and can at all frequencies used be made to inject a current of the same magnitude with opposite polarity into the received signal node **Vrx**, thereby achieving a high transmission signal and transmission echo signal rejection from the received signal path.

The echo signal current into node **Vrx** is canceled as described below. There are two complementary methods of describing the echo signal. First, we could analyze the circuit using a nominal reference load impedance with an echo signal injected at the output port, the echo signal having a phase and amplitude derived from the parameters of the real life line. Secondly, we could analyze the circuit using a load having a frequency varying impedance. Therefore, when using the varying impedance load view, it is no longer necessary to consider an echo signal that is injected from the line into the balanced hybrid coupling circuit.

Because the hybrid branches are connected at low impedance points, there is no interdependency between the two complementary halves of the balanced hybrid coupling circuit since the hybrid branch from one half of the circuit connected to the other half of the circuit does not load the node where it is connected.

Additionally, the received signal is a signal that is injected from the line **16** to the input of the balanced hybrid coupling circuit at node **Vload** and injects signal current into node **Vrx** through resistor **R32**. The other hybrid branches do not inject any received signal current into node **Vrx** because the other hybrid branches are connected at the output of the Transmission signal line driver **2** that has an output impedance of zero. Accordingly, only the transmission signal **Vtx** exists at the output of the Transmission signal line driver **2** and there is no received signal cancellation through the other hybrid branches.

The balanced hybrid coupling circuit of the present invention advantageously utilizes a circuit topology with a relatively small number of components. The present invention may utilize passive components in the transmission echo reconstruction circuit in order to maximize linearity of the signals processed and minimize distortion. The present invention may also utilize passive components in the subtraction circuit. Accordingly, only the subtracted signal with the enhanced receive to transmit signal ratio enters the receive path amplifiers, thus minimizing distortion and maximizing the dynamic range of the receiver.

The present invention provides compensation for the transmission echo signal component produced by the line transformer. The present invention may also compensate for a high pass filter incorporated into the line transformer or connected to the line transformer by modeling the impedance of that filter as part of the load impedance. A simple RC network of the balanced hybrid circuit provides sufficiently effective echo compensation only when there is relatively slow variation of the line impedance and phase. High pass filters have a higher rate of change of impedance and phase as the order of the filter increases. A third order high pass filter can be compensated from frequencies slightly above the critical frequency and above. As the order of the

filter is increased, the frequency ranges compensated for will be much higher than the critical frequency and it will be a less effective hybrid circuit. In contrast, the present invention may compensate for the transmission echo effect of up to a third order line high pass filter which can include series capacitors at the primary (line side) and secondary (modem and hybrid side) of the transformer.

Additionally, the present invention may utilize the connection of two series RC branches that are connected between low impedance points, which cancels the interaction between the branches such that a change to one branch will not affect the other branch.

The system and method of the present invention are implemented in any number of communications or other related schemes where full duplex transmission over overlapping frequencies require the compensation for transmission echo signals, e.g., in embedded telecommunications systems, modems, and other wire-line and non-wireline signal transfer applications. The system may be implemented in embedded applications or as part of a larger data communications system.

While the invention has been described with reference to xDSL and ADSL modems connected to standard twisted pair copper telephone network, the invention is of course useful in other communications systems which require compensation for transmitted signal echo.

Although the preferred embodiments have been disclosed for illustrative purposes, those skilled in the art will appreciate that many additions, modifications and substitutions are possible without departing from the scope and spirit of the invention as defined by the accompanying claims.